Supply chain challenges and off-grid energy development: Insights from Southern and East Africa

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LETTER

Supply chain challenges and off-grid energy development: insights from Southern and East Africa

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Abstract

The off-grid energy sector, comprising small scale decentralised renewable energy systems, plays a growing role in electrifying underserved communities in many parts of Africa. However, development of the off-grid energy sector has suffered from underlying supply chain challenges, limiting the realisation of off-grid electrification potential in multiple contexts. This article examines the critical supply chain issues through accounts of practical challenges encountered by off-grid energy developers and service providers in Ethiopia, Malawi, and Mozambique. Insights generated for this article were derived through open-ended interviews and consultations with off-grid energy stakeholders and the authors' own experiences, corroborated with review of recent literature. The article discussed critical supply chain issues of locational dynamics; technological and financial challenges; and governance and regulatory issues hindering sustainable deployment and operation of off-grid energy projects through the account of three countries. It provides key recommendations to governments and stakeholders which include transforming import and customs procedures while strengthening transport infrastructure and intra-continental trade for off-grid energy components. The article suggests reduction in tariffs, high import duties and taxes on procurement of renewable energy components through a joined-up approach by public institutions aiming for long-term development. It emphasises the need for collective action by African states to invest in local infrastructure and workforce upskilling by developing specialised hubs and production facilities, strengthening local enterprise and boosting local economies while limiting dependence on external suppliers for accelerated uptake of off-grid energy systems in Africa.

1. Introduction

Many observers have suggested that the decentralised nature of small-scale off-grid renewable energy systems makes them less vulnerable to system disruptions as compared to centralised energy grids and networks, especially within sensitive ecosystems and areas vulnerable to climate shocks. These decentralised systems are often viewed as having more resilience to such shocks or disruptions, as a major disturbance in energy supply will only occur when multiple systems are affected simultaneously [1, 2]. Accordingly, along with the infrastructural and financial challenges of extending centralised grid networks in some contexts, the interest from state governments, energy planners, donors, and investors in scaling up small-scale off-grid systems to address energy poverty has grown considerably in recent years [3].

Deployment of off-grid renewable energy systems is particularly relevant for countries in Africa with low levels of electricity access, vulnerability to climate change, and large gaps in infrastructure provision [4, 5]. They also play a crucial role in contributing to international and country-specific climate and development policy objectives while improving urban and rural livelihoods locally [4].

However, commissioning of solar home systems (SHS), community microgrids, and other distributed renewable energy systems requires specialised components and equipment, making them reliant on globalised and networked supply chains. These dynamics raise tensions between ideals of self-sufficiency and the realities of dependence, and between dynamics of connection and disconnection, within off-grid systems and their surrounding communities [6, 7].

The underlying challenges concerning supply chains for sourcing components for development and operation of off-grid energy systems have gained salience for project developers, managers and user communities, in terms of both the demand and supply sides of the value chain [8–10]. Growing complexities of a volatile international market coupled with exogenous factors and trends, such as the Covid-19 pandemic, climate change, financialisation, the Russia–Ukraine war, amongst others have impacted the development of off-grid energy systems. These challenges not only result in uncertain delays in the delivery of projects but also incur huge losses to project developers owing to price fluctuations [11, 12]. Perceived uncertainties and high investment risks associated with supply chain barriers discourage off-grid renewable energy developers to scale their businesses in potential areas. Lack of credit for customers of solar and other off-grid energy systems provided through states or system developers creates further gaps in market demand among local communities.

While an extensive literature examines the role of supply chains or global value chains in fostering global production and innovation capabilities, few researchers have examined the implications of supply chain challenges for the localised and distributed off-grid energy sector [13, 14]. This article investigates the critical supply chain challenges faced by the off-grid energy sector in most of the least electrified countries in Africa through reflections from Ethiopia, Malawi, and Mozambique. The article examines contemporary supply chain issues through a practitioner-informed multi-country synthesis. These issues vary from financial constraints, reliance on imported technologies, unevenly applied customs duties, lack of local manufacturing capabilities, fragmented governance, lack of regional cooperation to locational dynamics. The article proposes a set of recommendations for policy makers, public institutions, and intergovernmental organisations to overcome existing supply chain barriers for scaling up off-grid renewable energy systems in Africa.

2. Methodology and conceptual framing

The insights to examine critical supply chain challenges for off-grid energy systems were derived through open-ended interviews and consultations with off-grid energy developers and service providers during field visits and a series of workshops held between 2022 and 2024, corroborated through review of scholarly and grey literature. Authors interviewed 15 off-grid energy developers and managers in three countries, six in Malawi, four in Mozambique and five project stakeholders in Ethiopia. All of the respondents were in the profession of deploying and managing off-grid energy systems powered through solar and micro-hydro based technologies for 5–10 years.

The respondents were asked open-ended questions across the dimensions of locational challenges, technological and financial issues, and governance and regulatory barriers in sourcing equipment for off-grid energy systems. Authors carried out the thematic analysis by manually evaluating the responses across broader dimensions and further categorised barriers under the sub-themes of local manufacturing, unstructured sourcing of equipment, high import duties, and customs clearance within the dimensions of technological, financial and regulatory issues.

These barriers are particularly relevant to different stages of the supply chain including production, transportation, customs, procurement, deployment, operations and maintenance. For example, barriers related to geographical location and lack of local manufacturing and production facilities directly impact production and transport stages of the supply chain. Similarly, issues related to financial constraints, customs clearance, unstructured sourcing of equipment and import duties are particularly relevant at the stages of customs, procurement, deployment and operations, as shown in figure 1. These challenges and their linkages with different stages of the supply chain are explained in detail in subsequent sections followed by key policy recommendations.

Anonymised quotes from the responses of off-grid energy developers and managers are included in subsequent sections to reflect their perspectives for different supply chain issues. Since the impact of different supply chain issues varies with respect to the three countries as per their geography, social and political landscape, some of the challenges proved to be crucial with respect to a particular country. Although authors tried to balance the representation of each of the three countries for different categories of challenges, there might be instances where one country appears to be affected more by multiple challenges.

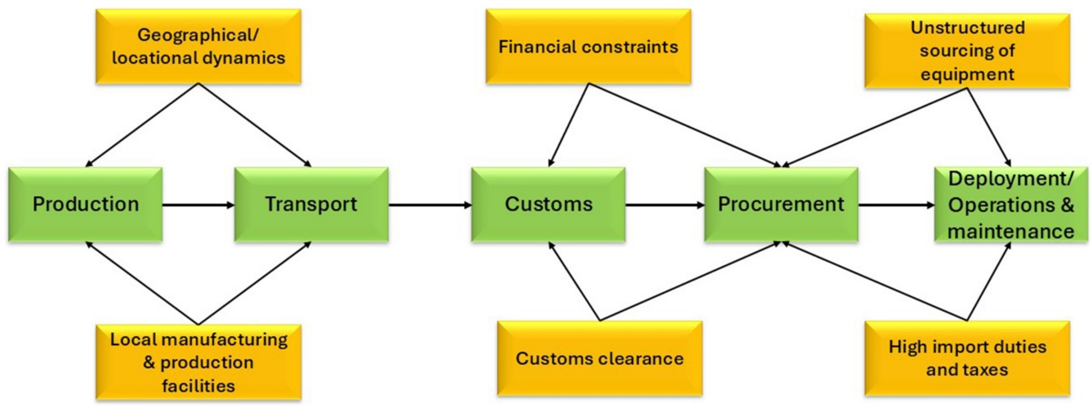

Figure 1. Conceptual framing linking key barriers with different stages of supply chain (*Source*: Authors' own).

3. Supply chain challenges hindering off-grid energy development across countries of Southern and East Africa

This section explains the critical supply chain barriers affecting the development of off-grid energy sector across Ethiopia, Malawi, and Mozambique. This includes geographical challenges stemming from the countries' location with respect to seaports and locational dynamics of global production networks governing the supply chain of off-grid energy equipment. It also sheds light on the supply chain disruptions faced by vulnerable geographies owing to climate change induced risks and unforeseen events. The section further explains technological and financial issues including lack of local manufacturing, unstructured sourcing of equipment and the persistent foreign exchange (forex) crisis. It also addresses the governance and regulatory issues of high import duties and taxes for energy sector components and bureaucratic hurdles including customs clearance for the procurement of components.

3.1. Geographical/locational dynamics

Within mainstream economic development studies, there is a broad agreement that economic growth and dynamism are underpinned by multiple social and institutional factors often referred to as 'business climate.' Such a business or investment climate is influenced by economic policies and political-institutional factors as much as by geographical and ecological endowments. Nevertheless, locational challenges have shaped a broad range of industries, among them the off-grid energy sector in African contexts. For instance, Africa's landlocked states must rely on neighbouring countries for shipping and transportation connections to import goods. This adds to the cost of off-grid renewable energy equipment and to shipping times, owing to additional layers of custom clearance and varying modes of transport [8]. For instance, project developers in Malawi rely on the ports of Beira or Nacala (Mozambique), Durban (South Africa) and Dar es Salaam (Tanzania) for importing bulky equipment.

Ethiopia depends on Djibouti's port facilities for nearly all of its imported goods [15]. The poor road infrastructure and limited transportation options within Ethiopia increases the cost and complexity of moving imported technologies from Djibouti ports to project sites. With several seaports located along Mozambique's long coastline, off-grid developers in Mozambique still face multiple challenges in transporting equipment to remote and interior regions within the country due to limited and poorly maintained road infrastructure and challenging terrain. Lack of transportation facilities, poor roads, railways and other connective infrastructure adds complexity to sourcing components, replacement parts and suitable technicians to carry out repairs and maintenance [16].

Moreover, Ethiopia, Malawi, and Mozambique are prone to natural hazards and climate change induced risks including the rising frequency and intensity of cyclones, droughts and flooding. Cyclone Idai in 2019, for instance, caused severe destruction across parts of Mozambique and Malawi resulting in 1593 deaths and displacing millions [17]. It not only damaged houses and crops but also harmed major infrastructure in Mozambique [18]. Tropical storm Ana damaged Malawi's national hydroelectric dam and caused the shutdown of the Kapichira Power Station, a central power generation utility, resulting in the loss of 30% of generation to the national grid in 2022 [19]. Such unforeseen disruptions damage physical infrastructure while creating long-term harm to less visible but equally critical equipment supply chains for energy services projects [20].

On the supply side, China has become the principal source country for many manufactured goods in Africa [21, 22]. In some cases, Chinese imports have replaced locally manufactured products while others compete against imports from countries outside Africa [23]. In particular, in recent years, the production of solar PV components has become increasingly geographically concentrated in China. Although this has contributed to substantial manufacturing cost reductions and enabling scale up of renewable energy globally, this concentration of the supply chain also presents challenges and tensions [24, 25].

After decades of investment, 70% of silicon, 79% of polysilicon, 97% of silicon wafers, and 85% of solar cells were manufactured in China in 2021, with its share of worldwide production of solar components expected to reach 95% by 2025 [24]. One such challenge is the rise in frequency of trade-related disputes, via the World Trade Organization and domestic trade remedy channels, resulting in import tariffs, counter tariffs and other trade barriers enacted across the sector during the past decade [26, 27]. Another challenge concerns recent accusations that solar supply chains rely on forced labour programmes in Xinjiang in western China, with a lack of transparency and traceability [25].

Solar PV module assembly is more geographically dispersed as compared with components manufacturing. However, large module assembly plants located in southeast Asia (Vietnam, Thailand and Malaysia) are mostly operations of subsidiaries of Chinese-headquartered firms, with China reaching a global market share of 75% for module assembly [25]. Suggesting growing opportunities for dispersion of assembly operations, Mozambique's state agency for rural energy (FUNAE) operates a solar panel assembly plant in Beluluane industrial park outside the capital city, Maputo. The plant's output currently is used solely within FUNAE's solar PV projects in rural Mozambique. China has used similar strategies for building supply chains linked to the development of markets and absorption of technologies in wind power, concentrated solar power (CSP) and other renewable energy technologies [14]. Indeed, lessons from implementation of off-grid renewable energy projects in China show that strong networks of supply chain actors are vital for building local capacity [28].

3.2. Technological and financial issues

3.2.1. Lack of local manufacturing and production facilities

The development of a robust off-grid energy sector in Africa has yet to reach its full potential due to the scarcity of local manufacturing and production facilities, locking countries into low value-added activities and forcing them to forego environmental and labour standards [29]. Lack of technological capabilities, poor infrastructure, and an insufficient policy enabling environment further compound these challenges [11]. Presently, investment funds for renewable energy development are mainly oriented towards importing technologies and equipment rather than creating or supporting local manufacturing capabilities. This exposes African states to external shocks, such as extreme weather events and epidemics in faraway regions [6, 30].

The Covid-19 pandemic and subsequently Russia's invasion of Ukraine and conflicts in the Middle East have severely impeded supply chains for off-grid and grid-connected electrification projects in Africa, along with broader global energy shocks, destabilising oil and gas prices and threatening fuel shortages [31]. Partly as a result of these disruptions, Africa's population without electricity access increased by 4% in 2021 relative to 2019 [32]. Malawi and Mozambique broadly fit this trajectory, where scarcity of equipment severely hit the implementation of numerous renewable energy projects [33]. Our analysis through accounts of off-grid energy developers in Malawi indicates that almost every component for mini grids must be imported. Some components, such as conductors and insulators, are typically sourced from neighbouring countries including Zambia or Tanzania, and South Africa in the case of Mozambique. The experience is similar for SHS developers, as explained by an interviewee in Mozambique:

> '*We design our own systems, and we assemble them in China and then import them here to Maputo where they are already assembled. We have to do this because there is not a single factory here in Mozambique, so we cannot get anything here. What we have close to here, in South Africa, on a cost and pricing point of view it also doesn't make sense. There are no factories here, at least not for SHSs. So, we import everything from China and also from India in terms of solar irrigation systems.*'

Off-grid energy components such as PV panels, batteries, alternators, and transformers are frequently sourced from China, South Africa, and India [22, 25, 27]. It is relatively costly to import these bulky components due to high transportation costs and extended shipping times. In addition, 'balance of system' components, such as inverters, smart meters, switchgears, monitoring and billing systems need to be procured from producers in China, the UK, Germany, and the USA. Notably, most of the equipment sourced from neighbouring African countries is not manufactured in-house but rather assembled through the components sourced from other technologically advanced countries [34]. Further, the lack of a domestic market and local production facilities limits availability of spare parts for frequent repairs and maintenance of off-grid energy systems.

3.2.2. Unstructured sourcing of equipment

Notably, the challenges of sourcing equipment and consolidating global supply chains extends beyond installation to the operational phase due to unstructured sourcing of equipment [16]. Typically, many non-profit, donor-supported and community-based off-grid energy developers do not follow a standard approach or protocol to source critical equipment and machinery. They usually do not invite tenders or make terms of reference to ensure expected performance of equipment for its intended period of operation. Very often, they search online for the equipment they want to procure and select the least cost option apparently showing more features. An off-grid energy developer in Livingstonia, Malawi explained this process,

> '*I go to the internet and look for companies offering the product we need and just order from them.*'

Due to their unstructured procurement approach, off-grid developers often lack extended warranties, after-sales and end-of-life disposal services. This means the operators and end users need to self-manage repair and maintenance of equipment in case of a failure. Lack of spare parts, sophisticated design of some equipment, and their deployment in vulnerable settings add to the challenges for operators and community members to perform the repair services. This results in frequently procuring new devices even in cases of a minor fault or damage in the original equipment. An off-grid system developer in Malawi quoted,

> '*Repairing a transformer is very expensive. It is almost equivalent to buying a new one. Two years ago, lightning strikes damaged one of our transformers and it cost us around 3.5 million Kwacha to repair it.*'

Conversely, where off-grid operators can establish more structured ways of purchasing equipment, they face trade-offs in terms of quality standards and competitiveness. An off-grid operator in Mozambique explained that because they source goods that meet industry quality standards (including warranties), the unit prices are higher than products without the same quality assurances. This can make it difficult to compete with informal sellers since end-users need to be convinced of the value of paying a premium price for a higher quality product. One way that operators can try to mitigate this is to buy in bulk to reduce unit costs. However, this assumes that off-grid energy operators have sufficient cashflow for bulk purchases. This is often not the case, given many are still struggling to recover from recent (global) economic shocks and lack the institutional capacity or budgetary knowledge to access financial support that may be available [30].

3.2.3. Financial constraints

In recent years, the off-grid energy sector has been sharply affected by a financial crisis across much of the African region [35]. forex deficits across commercial and central banks, price volatility in dynamic international markets and inflation are some of the key financial constraints faced by project developers in procuring components from overseas [36]. These challenges not only led to delays in installation but also decreased profits due to rising prices of components [37]. Shortage of forex remains a critical issue for Malawi and other countries where exports lag behind imports owing to lack of resources and infrastructure [38, 39]. Central banks in these countries have political influence while prioritising usage of forex, where sourcing of renewable energy components does not hold a top position typically. Very often, extended clearance duration taken by central banks results in significant increases in components' cost owing to price fluctuations. An off-grid solar project developer in Malawi narrated this issue,

> '*I have had this issue when I was implementing the solar energy hub project in the south of Malawi. It's a 12.5 kW solar hub, with storage facilities and it powers 2-3 shops around it. That took us 4 months to get US$40,000 for the bank to clear it and give us the go ahead to purchase. Because of the forex shortages, automatically our currency is weaker. There is a lot of price fluctuation on the market. For instance, a product could be 1 million Kwacha, and the next week it is 1.4 million Kwacha.*'

The difficulties in obtaining forex needed for off-grid energy projects affects many African countries. For instance, commercial banks in Mozambique were facing a backlog of US$ 500 million towards their operations with foreign countries [40]. As a result, the Central Bank of Mozambique has imposed mandatory foreign currency reserves on all banking institutions in the country making it extremely difficult for businesses to make payments to import goods and services. The waiting time for an average forex transaction was extended to around three months in the latter half of 2024 [41]. Ethiopia also continues to experience shortages of foreign currency, hindering importers in securing the necessary funds to pay for importing technologies, leading to significant delays and cancellations of orders. Waiting time for the firms to get their forex requests processed by the banks was as high as six months [42]. Shortages of forex results in delays in project completion, increases in implementation costs and reduction in levels of investment. It further stimulates smaller or more informal operators to use the black market for arranging forex and encourages corruption, such as bribing banking officials to prioritise or speed up their payment process.

3.3. Governance and regulatory issues

3.3.1. High import duty and taxes on renewable energy components

Another critical issue faced by off-grid energy developers is the high import duty, taxes and fees for the procurement of energy generation equipment and components such as solar panels, inverters, batteries, transformers, generators, and meters from overseas. Inclusion of these charges has significantly raised the cost of components, ultimately affecting the price for the end users. For instance, import duties imposed on most of the renewable energy components and accessories in Mozambique ranged between (5–20)% in addition to 16% value added tax (VAT) [43]. After adding other import charges such as port handling fees, agent fees, etc, it results in a 35%–45% increase in cost of imported components, such as SHSs [44]. A solar off-grid energy developer in an interview with our team in 2022 observed,

> '*If we just do a quick analysis on the import duties and VAT, at the moment it represents about 45% of our costs. So, in the end this 45% is what the customer will pay.*'

Such high import duties and taxes imposed on energy sector equipment pose questions concerning the enabling environment and policies in countries with significant gaps in electricity access. Whilst there have been some recent efforts to address this, the devil remains in the implementation timelines, particularly given the pressures on states to raise tax revenues. For example, the Government of Malawi has exempted import duties on clean energy sector components to promote the deployment of renewables, yet 16.5% VAT remains in place on imports of majority components [45]. Similarly, the Government of Mozambique in August 2022 announced an economic stimulus package to temporarily exempt import duties on renewable energy products. Yet this has had limited impact on the sector to date. Firstly, the list of exempted equipment took many months of approval and secondly, it does not cover the full spectrum of equipment that off-grid energy operators need to assemble and supply their products [30, 46].

The situation is not different with respect to Ethiopia, where the Government waived duties on import of solar PV panels, batteries and inverters but still imposing duties ranging from (5–35)% on ancillary components such as charge controllers, electric cables and PV panel support rack/structures. Further, imports of all components are subject to 15% VAT and 3% withholding tax. Some of the components are subject to 10% surcharge and 3% social welfare levy duty in addition to VAT. Typically, the imposed duties, VAT, withholding tax and surcharge cumulatively accounts to (30–50)% of the system cost while procuring components for an off-grid renewable energy system [47]. This is impeding the progress of off-grid energy system development.

As many working in the sector understand, there is a pressing need for governments to impose duties for raising their revenues; however, many are frustrated at what they see as short-term decision-making. Some recent economic modelling studies clearly demonstrate the benefits that VAT and import duty exemptions on renewable energy imports would bring [30]. It will enhance economic activities and generate higher tax yields through other revenue streams, along with potential job creation in the value chain. However, this is not realised so far due to perceived lack of understanding and negotiating power among the different arms of government, namely ministries of energy, ministries of finance, tax and customs Authorities to take a broader development outlook and a joined-up approach.

Moreover, government tactics around VAT reimbursement adds more complexity for renewable energy companies and service providers. For instance, in Mozambique, the renewable energy developers and service providers could claim back the amount of VAT paid on some components through government agencies [48]. However, governments are often slow to reimburse VAT, so it remains a sunk cost for off-grid developers and service providers. As one interviewee from Mozambique noted,

Table 1. Key indicators reflecting financial and import challenges in the three countries.

Indicator	Mozambique	Malawi	Ethiopia
Import duty (% of equipment original price value)	5–20	Not applicable	0–35
VAT (% of equipment original price value)	16	16.5	15
Typical cost increases due to duties, taxes and import fees (% of equipment original price value)	35–45	16–20	30–50
Typical waiting time to access forex	4–12 weeks	12–24 weeks	4–24 weeks

> '*The energy operator is supposed to recover the VAT from the government but the government never pays or pays slowly so it ends up being an amount of money that ends up sitting in the government coffers and not being used by the operators, so it is a financial risk to the operator.*'

3.3.2. Customs clearance

Given the widespread importation of technical components, off-grid system managers and developers encounter further challenges with customs clearance for renewable energy equipment imports. The process can be complex and bureaucratic, involving various agencies and extensive documentation [49]. Consultation with stakeholders in Ethiopia revealed difficulties in importing solar energy technologies due to these customs procedures. The custom delays sometimes last up to eight months, resulting in increased cost of project by 30%–50% from the initial budget allocation. The customs clearance hold-ups are believed to stem from lack of technical proficiency among officials in accurately classifying and valuing solar equipment, resulting in misclassification, valuation errors, inconsistent regulation application, and avoidable delays. Despite on going anti-corruption efforts, it still poses a challenge in certain areas, causing further delays and higher costs in importing clean energy technologies. Overall, these hurdles impede the growth of the off-grid energy sector in potential settings [50, 51].

Table 1 compiles key indicators reflecting import duties, taxes and forex challenges in procurement of renewable energy equipment by off-grid energy developers and managers. Data for import duties and VAT were sourced from secondary sources and referenced in section 3.3.1. Data for typical cost increase and waiting time to access forex were derived through stakeholders' consultations corroborated with review of recent literature as referenced in sections 3.2.3 and 3.3.1.

4. Key policy recommendations

This section presents various actionable short-term and long-term recommendations to policy makers, public institutions and inter-governmental organisations for addressing critical governance and regulatory issues, financial and technological constraints, and geographical challenges affecting supply chain of off-grid energy sector with respect to the three countries.

4.1. Short-term interventions

4.1.1. Streamlining customs procedures and capacity building

Government intervention is required to introduce measures for simplifying the necessary documentation, enabling online platforms for customs declarations, and harmonising regulations which could significantly reduce delays and costs associated with the import of off-grid energy technologies and products. Providing specialised training to customs officials on the classification, valuation, and handling of off-grid energy products/technologies can improve efficiency and ensure consistent application of regulations. Additionally, mechanisms are needed for building capacity among regulators and quality assurance agencies to ensure safety and standards of off-grid energy components.

4.1.2. Addressing foreign currency shortages and corrupt practices

The lack of available foreign currency in many African countries is a huge challenge and is often caused by fragmented governance of domestic and regional economies. Implementing policies to improve access to foreign currency reserves will ensure that importers can pay for imported off-grid equipment without delay. African central banks and ministries of finance and trade should execute reforms to regional, multilateral trade and financial agreements to mitigate the forex crisis. Guarantee financing agreements such as investment project financing with deferred drawdown option (IPF-DDO), supported by World Bank and recently executed by Government of Malawi, enabled the country to import essential commodities amidst low forex reserves [52]. Such financial mechanisms would be instrumental in the case of Mozambique and Ethiopia as well, who are facing macro-economic difficulties with low forex reserves in their banks and financial institutions.

Moreover, financial measures such as new Forex Directive introduced by the National Bank of Ethiopia eliminates mandatory forex surrender requirements and allows exporters to retain and sell their forex earnings to strengthen interbank foreign exchange market. The new directive also eases repatriation of capital by foreign investors to attract foreign direct investment. Such monetary approaches and mechanisms would be a possible short-term solution to address the crucial forex crisis in respective countries [53, 54]. Further, governments should prioritise the procurement of renewable energy components over other competing sectors demanding forex. The slow and lengthy process at the customs offices is often linked to corruption and misuse of public funds. Enhancing transparency and accountability across customs and financial institutions can help mitigate the risks of corrupt practices and accelerate import of critical technologies.

4.1.3. Advanced procurement support

Renewable energy trade associations and clean energy organisations should constitute national level procurement agencies which could facilitate the demands of small off-grid energy developers and operators often scattered at different locations in a country. Such agencies could act like aggregators to pool the demands of renewable energy developers and operators to import components in bulk, thus saving shipping and procurement costs while ensuring product quality and standards. For instance, the demand for smart meters by various developers could be submitted to a national aggregator, which could import equipment using a structured procurement approach and ensure the warranty and after sales service from suppliers.

4.1.4. Reviewing tariffs, import duties, and tax policies

Governments often talk about minimising or eliminating tariffs, import duties and offering VAT exemptions for promoting the development of clean energy systems including off-grid energy systems. However, these policies have yet to materialise in many African countries, slowing the diffusion of off-grid energy technologies to rural communities, where they are most needed. Reducing or eliminating tariffs and taxes on off-grid systems' components would create an enabling environment for distributed energy systems, making it more affordable and accessible as indicated by most of the off-grid energy developers and managers in the three countries. Though the Government of Malawi has eliminated import duties on most of the renewable energy components, the VAT is still in place [45].

Similarly, Ethiopia waived off duties on import of PV modules, batteries, and inverters but duties and surcharge on import of ancillary components such as charge controllers, cables and PV panel mounting structures are still in place [47]. Governments should adopt a joined-up approach by improving cooperation between different stakeholders such as the Ministry of Energy, Ministry of Finance and Energy Regulatory Commission to design appropriate trade policies aimed for broader development beyond short term tax revenues. For instance, governments could raise taxes on carbon-intensive fuels to cross-subsidise tariffs and taxes on off-grid energy components.

4.2. Long-term interventions

4.2.1. Strengthening transportation and intra-continental trade

Considering the high levels of dependence upon importing technologies across the region, an immediate solution would be to invest in transport infrastructure and promote the development of efficient logistics services. Governments of landlocked states should establish regional collaboration protocols to ease the challenges of importing technologies. For example, Ethiopia has an uneasy relationship with neighbouring countries, such as Eritrea, affecting access to seaports and in turn slowing the import of energy technologies. Intergovernmental organisations in Africa should take collective actions to develop trade corridors to facilitate cross-border equipment transport while implementing multilateral trade agreements to promote duty free trade within the continent. Such measures would in turn reduce the transport costs and improve delivery times while supporting the broader aim of increasing clean energy adoption and addressing energy poverty.

4.2.2. Technical training and localisation of energy technologies

African economies cannot succeed entirely through dependence on imported technologies, notwithstanding the path dependencies and patterns of unequal exchange within the global economy [23, 55]. As indicated by off-grid energy developers and managers, lack of local market, production facilities and local workforce push them to import almost every component for the installation and maintenance of renewable energy systems. Lack of local manufacturing infrastructure even for sub-components and spare parts make them to rely on global production networks and supply chains to source components during incidents of scheduled maintenance or an unforeseen fault/ disruption. The unavailability of a locally trained workforce results in unexpected delays and additional costs burden in events of minor repairs and system upgradation.

Thus, relevant actors including energy companies, educational and financial institutions should look to strengthen pathways that help to develop local production and new industrial trajectories. This could reduce operational costs, create local employment and training of human resources with skill sets needed to engage in the clean energy transition [56]. This in turn facilitates the development of decentralised energy infrastructure while filling gaps in supply chains. Such efforts might include training of local residents to be installers, facilitators or part of maintenance teams through skills transfer [57].

Manufacturing of key clean energy technologies in Africa is currently limited to a handful of facilities, and domestic demand is almost seven times current production levels [58]. Strong demand is predicted to continue with solar PV installations expected to increase at an average compound annual growth rate of 30% by 2028 with a total of 23GW of additional capacity installed in 2025–2028 [59]. Recent investments show confidence in the viability of some local manufacturing, including Japan's Toyo establishing a 2GW solar cell plant in Ethiopia, which started production in 2025 [60]. However, individual African countries would struggle to establish manufacturing across the full solar PV value chain at present due to insufficient resources, capabilities, trade and finance. Undoubtedly, local manufacturers would face a tough competition with integrated solar system manufacturers in China and the Pacific East. Certainly, there exist challenges for local players to make manufacturing of solar components especially PV modules, financially competitive given the rapid decline in cost of PV modules and other equipment year by year in global markets [61].

A potential approach would be to begin with manufacturing of sub-components or 'balance of system' components, such as inverters, cables, mounting structures, etc which typically account for more than half of the solar PV system cost in many regions [62, 63]. This will have flow-on effects for capacity building by providing opportunities for training and user feedback on technology development within African countries. Additionally, local manufacturers may develop their infrastructural capacity to produce components of other renewable energy technologies apart from solar PV, such as biomass gasifiers, wind turbine components and micro-hydro generators, which often require customised design and fabrication as per the local context. For example, localised production of wind turbine components has been initiated in South Africa and Egypt. Egypt has successfully localised 30% of the wind farm components over the last few years and achieved 55% share of local manufacturing for CSP systems [64]. Local manufacturers in Africa may start with such facilities which do not include technological complexities and high-end investments in medium term and thereby build upon their capability to produce more advanced equipment in long-run.

Further, regional economic communities (such as AfCFTA[5], SADC[6], EAC[7]) and corridor management authorities (e.g. Nacala Logistics Corridor) may coordinate to develop a regional solar value chain strategy across Africa. This would establish a channel across countries with required mineral resources and those with technical capabilities in renewable energy components manufacturing [61]. In addition, governments might contemplate subsidising local production through price ceiling in line with local market prices, while other imported components would be unsubsidised. Another route for building capacity is knowledge exchange through higher education institutions, with a focus on local expertise and development of skills to harness emergent opportunities, along with raising awareness among end users on the types of renewable energy products available and consumer rights in relation to quality standards and safety [34, 65].

5. Conclusion

Although strategies needed to mitigate supply chain issues in each country are distinctive owing to their diverse geographies and political economies, still it is possible to identify common themes and areas to comprehend key recommendations. Sustainable uptake of off-grid energy systems needs a holistic policy, integrated systems and enabling environment, which should address the critical supply chain challenges

[5] AfCFTA: African Continental Free Trade Area.
[6] SADC: Southern African Development Community.
[7] EAC: East African Community.

within and across national boundaries. Countries should review their tariffs and tax policies on the import of renewable energy components. Malawi and Mozambique have taken some initiatives in this direction, but they must also follow ground implementation of exemption policies promoting the growth of renewable energy industries. Governments must strengthen their capacities to streamline customs procedures while providing dedicated procurement support to small scale off-grid energy developers and service providers. Moreover, financial institutions in the three countries should introduce financial agreements and monetary reforms such as IPF-DDO in Malawi and the new forex Directive in Ethiopia to address the immediate forex shortage.

There is a pressing need to explore opportunities for establishing local infrastructure across all the three countries, including stimulating market demand and addressing barriers for setting up solar equipment manufacture through a regional strategy. This could help to provide technical training to develop a skilled workforce and initiate manufacturing of balance of system components. Moreover, attention to supply chains is critical amidst recent global political tensions and increasingly protectionist actions that will alter trade patterns. African states can buffer against potential disruptions and realise additional benefits through collective actions, such as by developing specialised hubs for manufacturing particular components or technologies across the continent. For instance, South Africa, an emerging supplier of smart metering systems, could enhance its role as a specialised hub for supplying ICT (information and communications technologies) and monitoring products for off-grid developers in Africa. Moreover, Malawi, Mozambique and Zambia, each with rich mineral resources and relatively low costs of labour, have potential to establish specialised manufacturing hubs for engineering equipment such as motors, turbines and transformers.

Such actions require a strong collective approach between African states, firms, and investments in research and development as well as establishing international training and manufacturing facilities. Importantly, such joined-up action will enable the mitigation of logistics and transport gaps by developing dedicated trade corridors facilitating access to seaports to landlocked geographies, such as Malawi. Additionally, African governments can execute multilateral trade agreements to address critical financial and import issues while trading off-grid energy components within Africa. While the African Union's initiatives including the AfCFTA could be a major step towards enabling trade and production, their wider implementation is needed to link off-grid energy with other sectors, including education and health.

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Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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